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Matrilocality during the prehistoric transition to agriculture in Thailand?

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Stable isotopes in teeth are providing important correlations between ancient people and the geographical location of their childhood homes. In an exciting new application, the authors measured the varying signatures of strontium, oxygen and carbon isotopes in the teeth of a sequence of people buried in Thailand during the period of the introduction and intensification of agriculture. Preliminary results point to the arrival of immigrant men, followed by a change in the relationship between the sexes: the women grow up on local food, the men have access to more widespread resources. This perhaps implies a matrilocality system, where forager men raised elsewhere marry into farming communities. It provides a likely antithesis to the social consequences of introducing agriculture into central Europe.

Keywords: Southeast Asia, Neolithic agriculture, marital residence, strontium isotope analysis, oxygen isotope analysis

Method

Introduction

During separate Holocene events in Europe, Asia and the Americas, language, human genes and material culture seem to have spread with the practice of agriculture (e.g. Bellwood 2001; Diamond & Bellwood 2003; Renfrew 2000). In many areas of the world, agriculture appears to have spread through 'demic diffusion', that is, increases in population, and densities of population, that agriculture itself made possible (Ammerman & Cavalli-Sforza 1984), and languages and genetic similarity could also have spread through a similar demic process (Diamond & Bellwood 2003; Higham 1996; Renfrew 1987, 2000). But while demic diffusion may have predominated, it is equally important to assess the involvement, different for each place and time, of indigenous hunter-gatherers who adopted farming through contact with colonising farmers. For example in Neolithic Europe, indigenous adoption has been shown to have been substantial (e.g. Gronenborn 1999; Renfrew 2000; Price 2000; Zvelebil & Lillie 2000). The foragers and farmers may have exchanged raw materials and foods,

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but also marriage partners; the immigration of forager women into farming communities seems particularly likely (e.g. Bentley *et al.* 2003b; Cronk 1989; Spielmann & Eder 1994; Zvelebil & Lillie 2000). Inter-marriage between indigenous and colonising groups, explicitly considered by Ammerman and Cavalli-Sforza in their 'wave of advance' model (1984: 82-84) has been subsequently somewhat under-emphasised in discussions of demic diffusion.

Although there is a good case for demic diffusion as a mechanism by which agriculture spread from southern China into Southeast Asia, *c.* 6500 BC to 1000 BC (Bellwood 2001; Higham 2002), it also appears likely that contact with indigenous groups took place and was significant. As Higham (2002: 110-11) points out, '*In reality, . . . the situation between 2500-1500 BC was probably much more complex than the [demic diffusion] model might suggest at first sight. Any intrusive group entering Southeast Asia would have encountered long-established hunters and gatherers.*' In contrast to the rapid transition from hunting and gathering to farming in Central Europe, many communities in prehistoric Southeast Asia appear to have had the knowledge of cultivation for centuries without practising it intensively. In Thailand, the transition, having begun at least by the late third millennium BC, from hunter-gathering to small, sedentary communities with animal husbandry and knowledge of domestic crops, did not lead to intensive rice agriculture until much later, *c.* 1000 BC. During this prolonged transition, local foraging groups may have influenced the development of farming (Bellwood 1996).

A productive area of research into the prehistoric spread of agriculture is human population genetics. Currently, most genetic samples come from modern living people, so the ancestries of the *haplotypes* (groups of genetic similarity) must be extrapolated backward through probabilistic means that, although mathematically sophisticated, are necessarily inexact. Nonetheless, a surprising amount of information about the past is extracted from modern gene distributions. One example is the characterisation of marital residence patterns by comparing geographic patterns of human mitochondrial (mt) DNA, which is passed through the female line, with those of male-transmitted Y-chromosomes (e.g. Seielstad *et al.* 1998). In Thailand, the geographic distribution of Y-chromosome haplotypes from modern populations suggests that the earliest farmers of Thailand were migrants from China (Tajima *et al.* 2002), whereas evidence from human mitochondrial (mt) DNA suggests that some Thai ethnic groups share ancient maternal ancestors (Fucharoen *et al.* 2001). Although these indications may seem contradictory, a possible explanation is that indigenous, pre-agricultural communities in Thailand had been matrilineal, such that male migrants married into their brides' indigenous communities.

This, however, is only one possible explanation for why a more exogenous Y-chromosome pattern might coincide with indigenous mtDNA patterns (cf. Currat & Excoffier 2005). Ultimately, human population genetics provides no definite answer for how agriculture spread into Thailand. The problem is that evidence from sources such as the genes of modern people, archaeological sites and artefacts do not tell us directly how prehistoric people moved. What is needed is direct evidence from the skeletons of the people who were involved in the transition to agriculture. Unfortunately, skeletal-biological evidence from prehistoric Thailand is also equivocal, simultaneously showing both similarity with modern Thais and similarity with East Asians, particularly the Jomon people of Japan (Pietruszewsky & Douglas 2002: 254-5) and Shang Dynasty Anyang from China (Pietruszewsky 1997).

However, a more direct relationship between people and their geographic origin is provided by the analysis of certain stable isotopes contained in tooth enamel. In the research reported here, we used stable isotope analysis on the skeletal material, not only to infer mobility since childhood (e.g. Budd *et al.* 2004; Price *et al.* 2001), but to distinguish the relative mobility of the sexes. We report our measurements of strontium, oxygen and carbon isotopes in the tooth enamel from skeletons of the prehistoric people at Ban Chiang (2100 BC–AD 200), in northeastern Thailand in order to compare our results with the geographic signatures of the isotopes concerned. In this case the geographic control was provided by analyses of animal remains. The long-term goal is to acquire isotopic evidence from many different sites that witnessed the transition to agriculture in Southeast Asia (e.g. Bentley 2004), to enable us to test predictions concerning the prevalence of demic diffusion as opposed to, say, the immigration of forager females into farming communities.

The most compelling results from this particular study come from comparing the numbers of non-local strontium isotope signatures among males and females. We hypothesise from our results that a cultural transition to matrilocality occurred at Ban Chiang. While readers are invited to interpret the isotope data for themselves, this interpretation is consistent with inferences from genetics and linguistics that matrilocality has existed in Southeast Asia for millennia (Burton *et al.* 1996; Oota *et al.* 2001). If true, the contrast with skeletal-isotopic evidence for patrilocality in Neolithic Europe (Bentley *et al.* 2002), where the transition to agriculture occurred much more rapidly, suggests that prehistoric marital residence customs may have significantly affected how agriculture spread on different continents.

Ban Chiang site and skeletal sample

Ban Chiang is located in the Songkhram River watershed of the northern Khorat Plateau of north-east Thailand. The modern village is located on a large mound at the confluence of three streams at approximately 170m above sea level. The first excavations beneath the modern village were conducted in 1967 by Vidya Intakosai (You-di 1975), and further excavations by Nikhom Suthiragsa in 1972 (Suthiragsa 1979) yielded burials and evidence of bronze and iron metallurgy. In this study, we have utilised skeletal material from two Thai-American excavations, which were about 100m apart and covered about 0.16 per cent of the eight hectares of the village mound (Charoenwongsa 1982; Gorman 1977; Pietrusewsky 1997; Pietrusewsky & Douglas 2002; White 1982, 1986). The 1974 excavation, in the yard of a modern house, is referred to as the Ban Chiang (BC) excavation, and the 1975 excavation along a road is the Ban Chiang Eastern Soi (BCES) excavation.

These two cemeteries contained 142 inhumation burials – predominantly primary, supine and extended – which showed differences in orientation between the two burial sites: the predominant grave orientations during the early phases were along a north/south axis at BC and a north-north-west/south-south-east axis at BCES. From EPV, predominant grave orientations changed to a north-west/south-east axis at BC and a north/south axis at BCES. Grave furnishings included pottery, bone tools, clay pellets and beads, adzes, spear points, bracelets and anklets, as well as skulls and limbs of pigs and/or cows. The stratigraphic sequence of burials at Ban Chiang allowed us to define ten phases of burials grouped in

Table 1. Number of burials in Ban Chiang (BC) and Ban Chiang Eastern Soi (BCES) excavations, by phase. After (Pietrusewsky and Douglas 2002: Table 1.1)

Burial phase	BC burials	BCES burials	Period
LP X	4	6	Late Period
LP IX	0	5	300 BC–AD 200
MP VIII	1	1	Middle Period
MP VII	2	19	900 BC–300 BC
MP VI	8	2	
EP V	20	12	
EP IV	3	22	Early Period
EP III	0	14	2100 BC–900 BC
EP II	18	3	
EP I	1	0	
Total burials	57	84	

three periods within the date range 2100 BC–200 AD (Table 1, Pietrusewsky & Douglas 2002: 5).

It had previously been argued that the first settlement of Ban Chiang dates back to the fourth millennium BC (White 1982, 1986), and more recent AMS dates on rice chaff from burial pottery date the appearance of bronze (EP II/III) between 2100 and 1500 BC (White 1997). Radiocarbon determinations from Ban Chiang and nearby sites collectively led Higham (2002: 93, 133–4) to propose dates of 2300–1500 BC for the Neolithic period on the Khorat plateau. The prehistoric villagers of Ban Chiang had knowledge of domestication from the first settlement of the village, but they were not intensive farmers. Human skeletons (Pietrusewsky & Douglas 2002), animal remains (Higham & Kijngam 1979) and plant remains (White 1995) from Ban Chiang suggest the early inhabitants relied substantially on hunted game, fish and wild fruits for centuries, with increasing reliance on domesticated chickens, cattle, pigs and dogs through time, as well as cultivation of rice and yams. Cord-marked ceramics are present in the earliest Ban Chiang phases, and distinctive white-carinated ceramics appear in the Middle Period (first millennium BC), at which time water buffalo bones and iron implements, common accoutrements for intensified wet-rice agriculture, also appear (Higham 2002: 187). Palaeo-environmental evidence from during and after the middle phases of occupation at Ban Chiang is consistent with the intensification of rice agriculture (Higham & Kijngam 1979; Penny 1999; White *et al.* 2004).

The burials recovered at Ban Chiang had thus been interred over the course of 2000 years covering the transition period from hunting and gathering to agriculture in Southeast Asia (Pietrusewsky & Douglas 2002; White 1982). The physical anthropology of the Ban Chiang skeletons has recently been fully documented in a monograph by Pietrusewsky and Douglas (2002). The findings show a decrease in life expectancy over time, suggestive of a decline in health, as well as increases over time in dental enamel hypoplasia and adult cribra orbitalia, all of which are consistent with expectations generated by studies of agricultural intensification elsewhere in the world. On the other hand, there is no evidence in the Ban Chiang skeletal series for other changes expected with intensified agriculture; neither the

expected decline in adult stature nor the expected increases in fertility, dental caries, skeletal infection or traumatic injury (Pietrusewsky & Douglas 2002). Overall, these are indications of continuity in health of Ban Chiang's prehistoric inhabitants, suggesting a continuous reliance on a broadly based subsistence system (Pietrusewsky & Douglas 2002).

In general, the Ban Chiang cranial and dental non-metric traits suggest temporal and spatial consistencies between the BC and BCES locales and between the sexes, but there are some interesting inconsistencies. For example, the majority of individuals with winging of the central incisors are from BCES, and statistically significant sex differences in the frequencies of some cranial traits suggest that males may be more closely related to each other than to females (Pietrusewsky & Douglas 2002: 42). The skeletal evidence suggests both males and females led strenuous lives at Ban Chiang, but there is also evidence for a sexual division of labour. Most of the activity-induced indicators are found in males, such as osteoarthritis of the upper vertebral column, suggesting carrying loads on the head and neck, and osseous changes to the bones of the feet suggesting strenuous use of the feet and ankles.

Methods

In order to characterise patterns of human mobility at Ban Chiang, we measured strontium, carbon and oxygen isotopes in the second molar (crown complete between ages 7-8 years; Hillson 1997: 123) or third molar (crown complete between ages 12-16) from selected human skeletons. Criteria used to select individuals from the complete Ban Chiang skeletal and dental series include adult age, sex estimation, preservation of more than four teeth, preserved molars, an antimere for the selected tooth (that is, a tooth on the other side), and preservation of some infracranial bone. These criteria were occasionally relaxed to include noteworthy burials (e.g. interred in a flexed position, metal artefacts, etc.). The Ban Chiang samples include both a tooth and bone fragment from 16 males and 16 females, and a tooth from 9 males and 3 females for a total of 25 males and 19 females. Only two tooth samples are available for the later phases at the site (MP VIII-LP X), where a small number of well-preserved skeletons were excavated.

Sr isotopes

Unlike carbon and nitrogen, strontium isotope signatures ($^{87}\text{Sr}/^{86}\text{Sr}$) are conveyed, without measurably fractionating, from eroded rocks through soils and into the food chain. The details of how $^{87}\text{Sr}/^{86}\text{Sr}$ serves as a geologic/geographic signature in the mineral of mammalian tooth enamel are described elsewhere (e.g. Ericson 1985; Price *et al.* 2002). Although a 'local' range for the site can sometimes be defined as compared with the average $^{87}\text{Sr}/^{86}\text{Sr}$ in human bones from the site as a whole, it is better to measure $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ in human tooth enamel than in bone because enamel is highly resistant to biochemical alteration (e.g. Chiaradia *et al.* 2003; Hillson 1997; Hoppe *et al.* 2003; Horn *et al.* 1994; Koch *et al.* 1997; Price *et al.* 2002; Sharp *et al.* 2000; Trickett *et al.* 2003). While 'non-local' signatures should identify immigrants, one must be aware that isotopic 'locals' may have moved between similar geochemical provinces, and non-locals may have been based locally but collected a diet from beyond the local area, such as a mobile forager who was later buried in an agricultural community (Bentley *et al.* 2003a).

Oxygen and carbon isotopes

Oxygen isotope compositions ($\delta^{18}\text{O}$, relative to standard mean ocean water [SMOW]) in the environment depend upon the fractionation of ^{18}O vs. ^{16}O during evaporation, condensation and precipitation in the hydrologic cycle, with ^{18}O preferentially retained in the liquid phase. Determined largely by temperature, the mean annual $\delta^{18}\text{O}$ in precipitation depends on latitude and altitude (Bowen & Wilkinson 2002), but also on topographic relief, distance from large bodies of water and relative humidity. Animals take in much of their oxygen through precipitated water, such that geographic origins are reflected in enamel $\delta^{18}\text{O}$ values measured in the same species from the same regional environment to minimise $\delta^{18}\text{O}$ variation due to physiological differences (e.g. Balasse *et al.* 2002; D'Angela & Longinelli 1990; Kohn 1996).

Carbon isotopes (expressed as $\delta^{13}\text{C}$ on the PDB scale) fractionate during primary production of organic matter, with a set isotopic fractionation dependent upon whether a plant uses the C_3 or C_4 photosynthetic process, such that C_3 plants have $\delta^{13}\text{C}$ values between -23 and -34‰ , whereas C_4 plants have $\delta^{13}\text{C}$ between -9 and -17‰ (O'Leary 1988). Although $\delta^{13}\text{C}$ in consumer bone carbonate generally reflects that of the diet (DeNiro & Epstein 1978), fractionation of carbon isotopes is also related to photosynthesis, metabolism and temperature (e.g. Heaton 1999; Koch *et al.* 1994; van der Merwe & Medina 1991). One significant source of variation for $\delta^{13}\text{C}$ values is the 'canopy effect' in dense forests, whereby plants on the forest floor photosynthesize less and take up recycled CO_2 , such that $\delta^{13}\text{C}$ values in leaves and air decrease continuously from canopy top to forest floor by several per thousand (e.g. Heaton 1999; Krigbaum 2003; van der Merwe & Medina 1991). There can also be a slight altitude effect, as high altitude (over 1000m) plants adapted to lower partial pressure of CO_2 , show enrichment in plant ^{13}C by a few per mil, which is passed to the animals feeding at high altitude (Bentley & Knipper 2005; Sparks & Ehleringer 1997).

In this study we measured $\delta^{18}\text{O}$ in the carbonate (CO_3) component of tooth enamel because the analysis simultaneously recovers $\delta^{13}\text{C}$ and the procedure (Koch *et al.* 1997; Balasse *et al.* 2002) is considerably faster and easier than measuring $\delta^{18}\text{O}$ in the phosphate (PO_4) component (cf. O'Neil *et al.* 1994; Vennemann *et al.* 2002). Fortunately, the $\delta^{18}\text{O}$ values recovered from phosphate ($\delta^{18}\text{O}_\text{p}$) and structural carbonate ($\delta^{18}\text{O}_\text{sc}$) are offset ($\delta^{18}\text{O}_\text{p} - \delta^{18}\text{O}_\text{sc}$) by a constant value of about 8.7‰ (Bryant *et al.* 1996), meaning our measurements of the carbonate component can be compared with other measurements of phosphate component. For humans, $\delta^{13}\text{C}$ values in tooth enamel carbonate reflect an average of the whole diet, offset by -9.4‰ such that a pure C_3 vegetarian would have a $\delta^{13}\text{C}$ value of about -13‰ in enamel, compared with 0 – 1‰ for a pure C_4 diet (Ambrose & Norr 1993; Koch *et al.* 1994). However, carnivores, omnivores and herbivores in a region usually have similar enamel $\delta^{13}\text{C}$ values (Lee-Thorp *et al.* 1989).

Procedures

Using a developed procedure to purify Sr from about 5–20mg of intact enamel (Bentley *et al.* 2003a), we analysed $^{87}\text{Sr}/^{86}\text{Sr}$ using a thermal ionisation mass spectrometer (TIMS) at the Southampton Oceanography Centre (SOC). During the period of analyses, repeated

measurements of the NBS SRM-987 standard ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710248$) yielded an average $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.710252 ± 0.000015 (2 s.d., $n = 169$).

In order to measure carbon and oxygen isotopes, about 5mg of tooth enamel was mechanically cleaned of all dentine, powdered and soaked overnight in 5 per cent acetic acid to remove post-burial carbonate contamination (Koch *et al.* 1997). After rinsing in Milli-Q H_2O and drying, about 2mg of powdered sample was reacted with 100 per cent phosphoric acid at 70°C in individual vials in the Kiel III automated cryogenic distillation system, interfaced with a ThermoFinnigan Mat 253 gas-source mass spectrometer at the University College London Bloomsbury Environmental Isotope Facility. Repeated analyses of an in-house carbonate standard yielded a precision better than 0.1‰ (1 s.d.) for $\delta^{18}\text{O}$ and 0.05‰ for $\delta^{13}\text{C}$, while calibration to SMOW and PDB scales was via repeated analysis of the NBS 19 calcium carbonate standard.

Analysis and interpretation

The results of strontium, oxygen and carbon isotope analyses in archaeological tooth enamel samples are shown in Table 2 for humans and Table 3 for fauna. In an effort to determine the local $^{87}\text{Sr}/^{86}\text{Sr}$ range for Ban Chiang, we measured a small sample of the human bones, but the narrow range of bone values (mean = 0.71343 ± 0.00017 , $n = 5$) does not overlap with any of the tooth values, suggesting the bones have been contaminated with groundwater strontium. At this point, the best indication of the ‘local’ $^{87}\text{Sr}/^{86}\text{Sr}$ range should be any consistent cluster of human enamel values through time.

Ban Chiang is situated on the Khorat Plateau in north-eastern Thailand, which is underlain by Jurassic shallow-water sandstones and shales and overlain by evaporated salt deposits (Workman 1977: 14–5). Mapping isotope signatures is a long-term project involving strontium- and oxygen-isotope analysis of hundreds of archaeological faunal samples from the region (cf. Bentley *et al.* 2004). The beginnings of our regional sampling show, for example, that archaeological dogs and deer from Ban Na Di, just 23km south-west of Ban Chiang, have $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\delta^{18}\text{O}$ signatures distinct from Ban Chiang humans, dogs and deer (Figure 1). In addition to this geographic separation, the fauna separate by species in $\delta^{13}\text{C}$ values (Table 3), with $\delta^{13}\text{C}$ around -2‰ for the open-country grass-feeders *Cervus porcinus* (hog deer) and *Cervus eldi* (brow-antlered deer) and around -12‰ to -13‰ for *Muntiacus muntjak* (barking deer), which ‘feed on the edges of forest or in abandoned clearings’ (Lekagul & McNeely 1977: 676).

Concerning the human tooth enamel values, three significant patterns emerge from the isotope values: (1) There is substantial variation in values within the sampled population; (2) there are significant differences between females and males, including an abrupt change in the chronological phase EP V, during and after which there is significantly less variance in the female $^{87}\text{Sr}/^{86}\text{Sr}$ values than in the male $^{87}\text{Sr}/^{86}\text{Sr}$ values; and (3) the distributions of values from the two different Ban Chiang excavation locales differ significantly.

Variation within the sampled population

Over all chronological phases, the mean $^{87}\text{Sr}/^{86}\text{Sr}$ in Ban Chiang human tooth enamel samples is 0.71173 ± 0.00061 ($n = 41$, excluding outlier BCES 1) among both sexes,

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Table 2. Isotope values in tooth enamel from Ban Chiang human skeletons. Measurement errors in the last digits (± 2 s.d) are shown in parentheses

Burial ID	Sex	Phase	Age at death	Tooth	$\delta^{18}\text{O}$ (SMOW)	$\delta^{13}\text{C}$ (PDB)	$^{87}\text{Sr}/^{86}\text{Sr}$
BC 05	Male	EP V	Middle aged	Mand L M3	27.86 (10)	−13.11 (15)	0.712211 (10)
BC 07	Male	EP V	Middle aged	Max R M3	27.29 (08)	−13.89 (10)	0.713311 (11)
BC 11	Female	MP VII	17-23	Mand R M2	27.99 (09)	−13.59 (10)	0.712902 (11)
BC 12	Male	EP V	Middle aged	Max R M3	24.72 (17)	−13.25 (26)	0.711889 (11)
BC 16	Female	EP V	20-30	Max L M1	27.98 (11)	−14.29 (06)	0.711904 (13)
BC 19	Female	EP V	Young adult	Max L M2	27.24 (07)	−13.76 (10)	0.71167 (11)
BC 20	Male	MP VI	35-40	Max R M2	25.72 (11)	−13.59 (07)	0.711721 (11)
BC 23	Male	EP V	45-50	Max L M2	25.20 (19)	−12.93 (19)	0.710696 (20)
BC 24	Female	EP II	Old	Max R M1	26.78 (12)	−14.09 (12)	0.712562 (11)
BC 25	Male	EP II	12-15	Mand L M2 (?)	26.35 (11)	−13.46 (07)	0.711251 (11)
BC 34	Female	EP II	40-45	Mand R M2	26.02 (08)	−13.62 (13)	0.711559 (10)
BC 35	Male	EP V	40-50	Mand L M2	26.87 (14)	−13.86 (08)	0.711042 (11)
BC 41	Female	EP II	35-40	Mand L M2	27.79 (07)	−13.25 (09)	0.711621 (16)
BC 43	Male	EP II	35-40	Max R M2	27.41 (08)	−13.80 (10)	0.710593 (11)
BC 45	Female	EP II	18-22	Mand L M2	26.89 (11)	−13.40 (08)	0.710976 (10)
BC 47	Male	EP II	25-30	Max R M2	27.51 (15)	−13.35 (06)	0.711514 (11)
BCES 01	Female	LP X	18-22	Max L M2	24.71 (05)	−13.65 (07)	0.725876 (10)
BCES 02	Male	LP X	35-40	Mand L M2	27.34 (16)	−13.23 (09)	0.713043 (10)
BCES 19	Female	MP VII	30-35	Mand R M2	27.61 (07)	−13.35 (12)	0.711559 (13)
BCES 22	Male	MP VII	Middle aged	Mand R M3	27.00 (16)	−13.79 (04)	0.711402 (11)
BCES 24	Male	MP VII	30-35	Max R M2	27.41 (14)	−13.36 (08)	0.711361 (11)
BCES 27	Female	EP V	35-40	Mand R M2	27.28 (09)	−13.81 (10)	0.712009 (11)
BCES 28	Female	EP V	35-40	Max L M2	28.17 (08)	−13.81 (13)	0.711971 (16)
BCES 29	Female	EP V	18-20	Mand R M2	26.29 (09)	−13.54 (05)	0.711770 (11)
BCES 31	Male	EP IV	45-50	Max L M3	27.50 (10)	−12.27 (03)	0.711099 (11)
BCES 33	Female	EP V	25-30	Mand R M2	26.28 (08)	−13.54 (08)	0.711823 (11)
BCES 34	Female	EP IV	25-30	Mand L M2	26.68 (08)	−11.80 (05)	0.712895 (10)
BCES 35	Male	EP IV	45-50	Max L M3	25.46 (07)	−13.61 (09)	0.711720 (11)
BCES 46	Female	EP IV	45-50	Mand R M3	26.51 (12)	−13.98 (12)	0.712017 (11)
BCES 47	Male	EP III	45-50	Mand R M3	27.23 (13)	−13.65 (09)	0.711798 (11)
BCES 50	Male	EP IV	25-30	Mand R M2	28.17 (20)	−13.74 (06)	0.711555 (13)
BCES 51	Male	EP IV	40-45	Mand R M2	26.76 (08)	−13.08 (12)	0.710553 (11)
BCES 55	Male	EP IV	14-16	Max L M2	28.03 (09)	−13.62 (15)	0.711818 (11)
BCES 56	Male	EP V	45-50	Mand R M2	25.99 (19)	−12.82 (11)	0.711776 (11)
BCES 57	Female	EP II	Middle aged	Mand L M2	25.91 (12)	−13.65 (12)	0.711936 (11)
BCES 59	Female	EP V	45-50	Max L M3	25.77 (09)	−13.13 (12)	0.711463 (11)
BCES 65	Male	EP III-IV	40-45	Mand L M2	28.08 (06)	−13.08 (08)	0.712067 (20)
BCES 72	Male	EP II-III	35-40	Mand R M2	27.05 (09)	−13.51 (12)	0.711558 (11)
BCES 73	Male	MP VII	35-40	Mand L M2	26.60 (12)	−13.42 (18)	0.711254 (11)
BCES 74	Male	EP II	Mid/old-aged	Mand R M1	26.45 (13)	−13.32 (14)	0.712008 (11)
BCES 76	Male	EP III	25-30	Max L M2	28.48 (13)	−13.63 (21)	0.712130 (11)
BCES 79	Female	EP II-III	Middle aged	Mand L M2	25.95 (10)	−13.24 (07)	0.711242 (10)

0.71188 ± 0.00054 ($n = 16$, excluding BCES 1) among females and 0.71163 ± 0.00066 ($n = 24$) among males. At this early stage of mapping the regional $^{87}\text{Sr}/^{86}\text{Sr}$, we note that the Ban Chiang human $^{87}\text{Sr}/^{86}\text{Sr}$ values are more variable than values in humans from the

Table 3. Isotope values in tooth enamel from archaeological fauna. Measurement errors in the last digits (± 2 s.d) are shown in parentheses

Lab #	Site	Species	$\delta^{18}\text{O}$ (SMOW)	$\delta^{13}\text{C}$ (PDB)	$^{87}\text{Sr}/^{86}\text{Sr}$
BCF 02	Ban Chiang	<i>Canus</i> sp (dog)	27.85 (12)	-11.71 (11)	0.712194 (13)
BCF 03	Ban Chiang	<i>Canus</i> sp (dog)	28.02 (16)	-11.85 (08)	0.712319 (13)
BCF 06	Ban Chiang	<i>Muntiacus muntjak</i> (deer)	24.88 (12)	-13.46 (14)	0.713408 (12)
BCF 01	Ban Na Di	<i>Canus</i> sp (dog)	31.33 (09)	-11.96 (16)	0.714113 (14)
BCF 04	Ban Na Di	<i>Canus</i> sp (dog)	29.95 (11)	-12.27 (07)	0.711581 (30)
BCF 05	Ban Na Di	<i>Cervus eldi</i> (deer)	30.93 (13)	-1.99 (10)	0.711610 (11)
BCF 06	Ban Chiang	<i>Muntiacus muntjak</i> (deer)	24.88 (11)	-13.46 (15)	0.713408 (11)
BCF 07	Ban Na Di	<i>Muntiacus muntjak</i> (deer)	28.30 (04)	-12.29 (02)	0.709437 (13)
BCF 08	Ban Chiang	<i>Cervus porcinus</i> (deer)	28.72 (05)	-1.58 (02)	0.714327 (13)
BCF 09	Ban Chiang	<i>Cervus porcinus</i> (deer)	36.28 (04)	1.69 (03)	0.715885 (11)
BCF 10	Ban Chiang	<i>Cervus porcinus</i> (deer)	26.24 (05)	-2.74 (03)	0.713735 (11)
BCF 11	Ban Chiang	<i>Sus scrofa</i> (pig)	30.10 (09)	-12.26 (05)	n.d.
BCF 12	Ban Chiang	Bovid	26.66 (03)	-1.92 (02)	0.714668 (57)

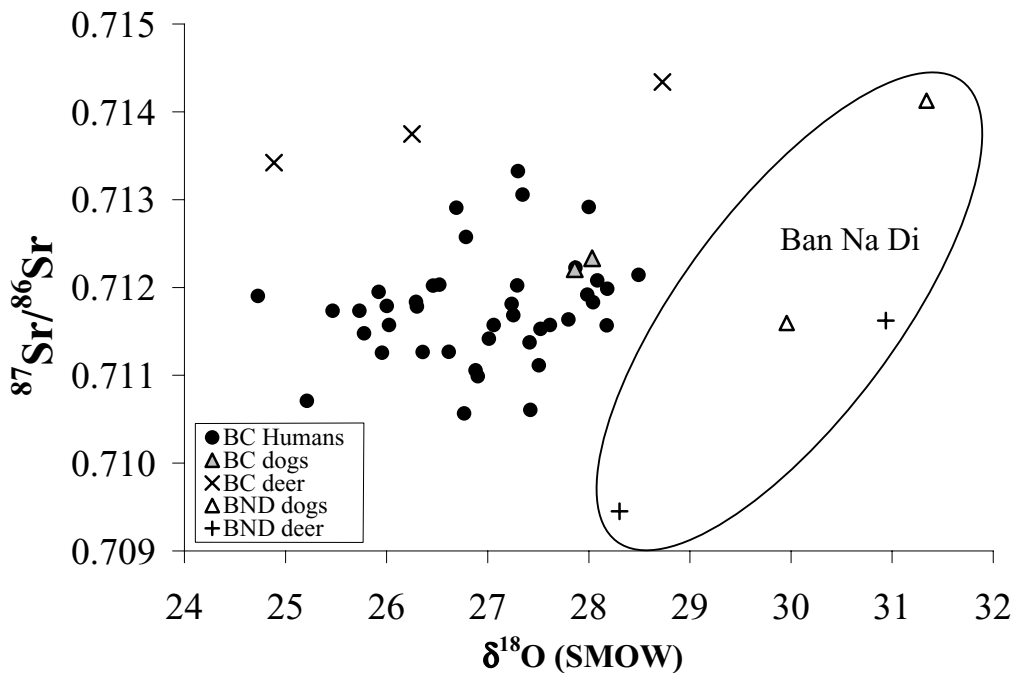
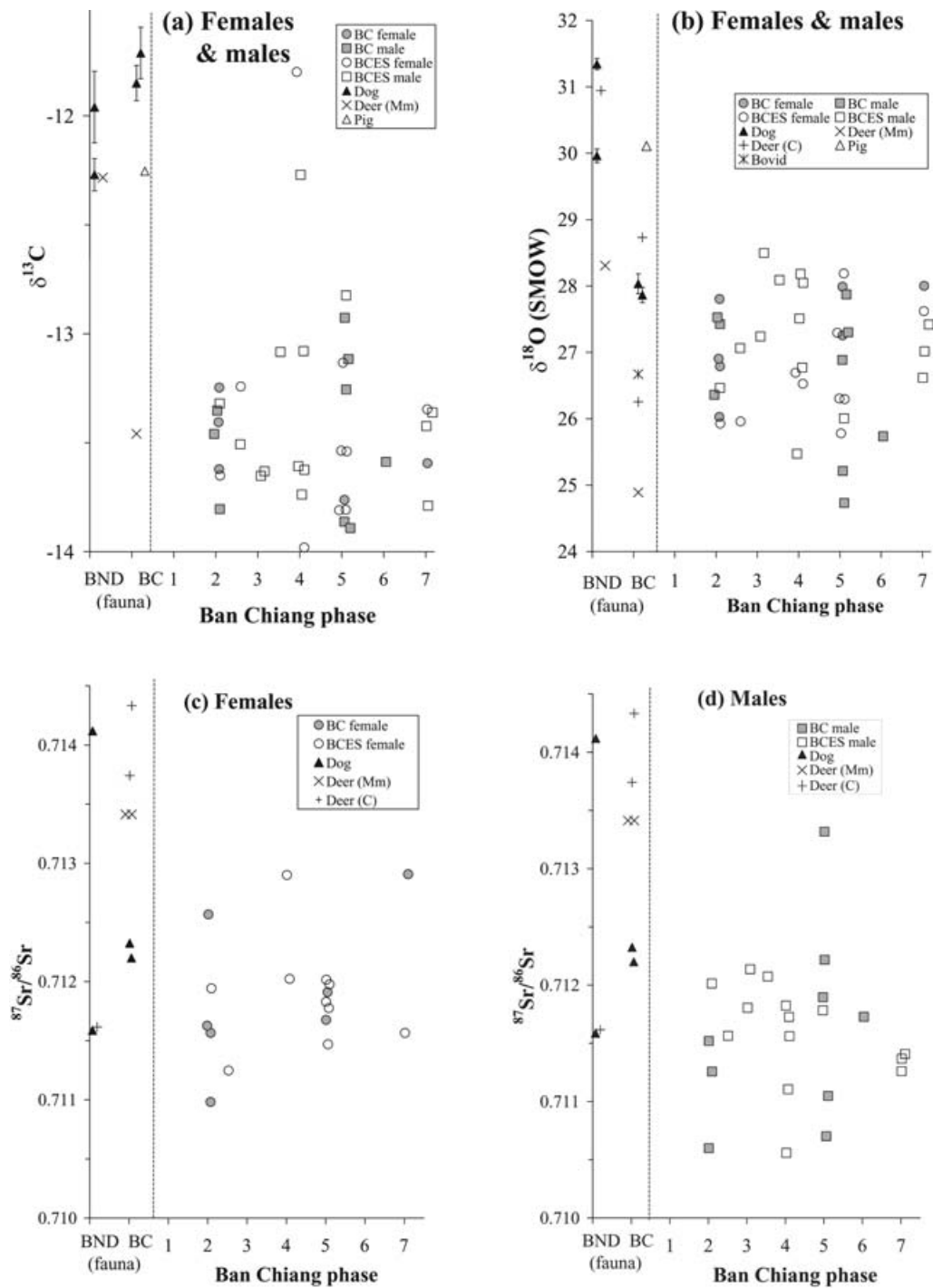


Figure 1. Strontium- and oxygen-isotope values in Ban Chiang (BC) and Ban Na Di (BND) samples.

coastal site of Khok Phanom Di, Thailand (0.70938 ± 0.00015 , $n = 68$, Bentley 2004). The $^{87}\text{Sr}/^{86}\text{Sr}$ values from two Ban Chiang dogs (0.71219, 0.71232) were within the 1σ human range, while the values from Ban Chiang deer were higher and more variable (0.71434 ± 0.00110).



The average $\delta^{13}\text{C}$ value over all chronological phases at Ban Chiang is $-13.5\text{‰} \pm 0.4$ among all humans – consistent with a diet of C_3 foods – and practically the same among females ($-13.5\text{‰} \pm 0.4$) and males ($-13.4\text{‰} \pm 0.4$). The $\delta^{13}\text{C}$ values from EP IV ($-13.2\text{‰} \pm 0.8$, Figure 2a) show significantly greater variance than from the other phases ($p < 0.001$, two-sample F -test). In contrast, the $\delta^{13}\text{C}$ values from EP II ($-13.6\text{‰} \pm 0.3$) are slightly lower and significantly less variable. As a reference, we can compare these ranges to those in Neolithic human teeth from Niah Cave, Borneo, for which the mean $\delta^{13}\text{C}$ is $-13.2\text{‰} \pm 0.8$ (Krigbaum 2003: Table 5). Compared with Niah Cave, the mean $\delta^{13}\text{C}$ values at Ban Chiang EP IV are identical, while those for EP II are slightly more negative and significantly more variable ($p < 0.003$, F -test).

The mean $\delta^{18}\text{O}$ among Ban Chiang humans is $27.1\text{‰} \pm 1.3$, and as with the carbon isotopes, the $\delta^{18}\text{O}$ values for Ban Chiang EP II ($26.8\text{‰} \pm 0.7$) and EP VII ($27.3\text{‰} \pm 0.5$) are less variable (Figure 2b). Since these $\delta^{18}\text{O}$ values are only a few per thousand different than in Neolithic humans from northern Borneo (22.5–26‰, Krigbaum 2003: Table 5), $\delta^{18}\text{O}$ may be of limited effectiveness for geographic ‘sourcing’ in this part of the world.

In sum, the isotope values among the Ban Chiang humans show high variance over all phases, but with significantly less variation among all three isotopes in and after MP VII. This probably reflects a broadly based subsistence regimen at Ban Chiang, also indicated by palaeobiological evidence (Pietruszewsky & Douglas 2002) at least until MP VII, when the restricted isotopic variance may reflect the intensification of agriculture. However, a restricted range of $\delta^{13}\text{C}$ values is also observed in EP II, while greater variation returns in EP V. This may imply some oscillation in agricultural dependence over time, as is quite possible in this part of the world (cf. Hoffman 1984; Griffin 1984; Headland & Reid 1989; Oota *et al.* 2005).

Differences between females and males

One of the most striking results of this study is that the range of $^{87}\text{Sr}/^{86}\text{Sr}$ values narrows considerably among females during and after EP V (Figure 2c), while simultaneously remaining wide among males (Figure 2d). In EP V alone, the variance in $^{87}\text{Sr}/^{86}\text{Sr}$ is significantly smaller for the females than for the males ($p < 0.001$, two-sample F -test). Although female $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values do not show a constriction in variation during EP V (Figures 2a and 2b), the mean $\delta^{13}\text{C}$ value is fairly significantly ($p < 0.12$) less negative for EP V males ($-13.30\text{‰} \pm 0.46$) than for EP V females ($-13.70\text{‰} \pm 0.35$), with the less negative values possibly deriving from open environments without canopy effect and/or from high altitudes.

Most of the exceptional human isotope values from Ban Chiang come from males. As shown in Figure 3, the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ measurement of all the human tooth enamel samples

Figure 2. Isotope values in human tooth enamel over the first seven chronological phases at Ban Chiang. Male and female values are combined for the oxygen isotope (a) and carbon isotope (b) plots, while strontium isotope values are shown separately for females (c) and males (d). To the left of the dotted line are values from archaeological fauna recovered at Ban Chiang (BC) and nearby Ban Na Di (BND). While the *Muntiacus muntjak* (Mm) species of deer are shown in both plots, the *Cervus* (C) species is not shown in (c) because the $\delta^{13}\text{C}$ values are well above the scale (as for the bovid). Grey triangles show values from two dogs excavated at Ban Chiang, with error bars showing typical \pm s.d. for all points whose error bars are not shown (to avoid clutter).

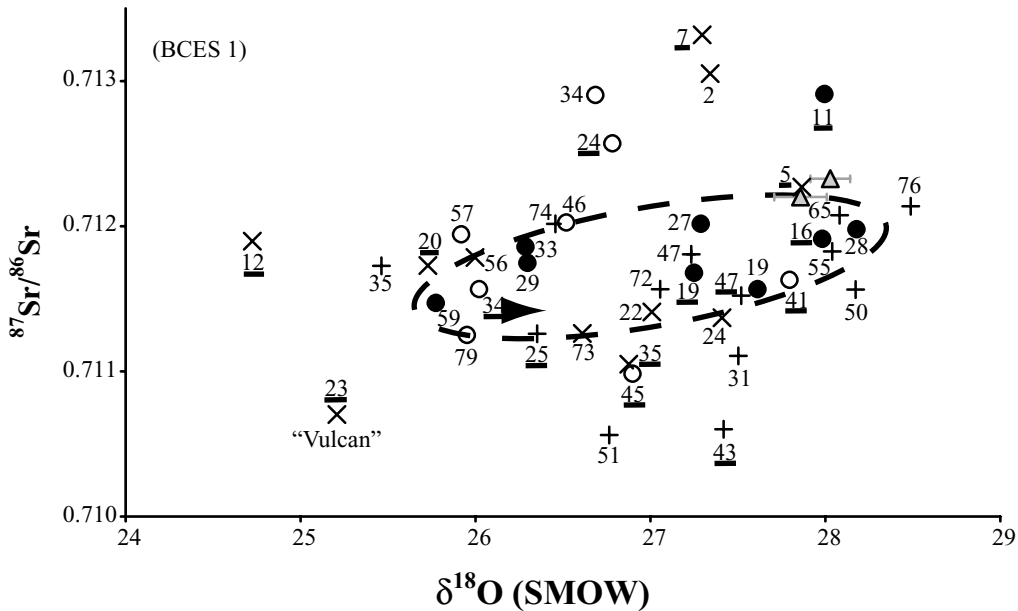


Figure 3. Strontium- and oxygen-isotope values in Ban Chiang skeletons. Each symbol represents a tooth enamel sample from a different human individual, and the dashed circle encompasses values from EP V females. Burial numbers from the BC locale are underlined, the others are BCES burial numbers. One outlier (BCES 1) is not shown. Crosses, males before EP V; open circles, females before EP V; X's, males during and after EP V; Filled circles, females during and after EP V. As in Figure 2, error bars (\pm s.d.) are plotted for the dogs only.

is from BCES 51, a male aged 40-45 years old, from EP IV. The second-highest value (BC 7, $^{87}\text{Sr}/^{86}\text{Sr} = 0.71331$) is also from a middle-aged male, from EP V. Although identified by different isotopes, it is significant that both BC 23 and BCES 76 appear to have non-local signatures (Figure 3), because they are among the small group of adult burials with metal implements (BC 23, BCES 7, BCES 24 and BCES 76). Burial BC 23 (EP V), with exceptional values for $^{87}\text{Sr}/^{86}\text{Sr}$ (0.71070), $\delta^{18}\text{O}$ (25.2‰) and $\delta^{13}\text{C}$ (−12.93‰), is an older (45-50 years at death) male nicknamed ‘Vulcan’ because he was found with a cache of clay pellets, a socketed bronze adze head and four bronze bracelets. Burial BCES 76 (EP III), with the highest $\delta^{18}\text{O}$ value (28.5‰), contained the earliest identifiable bronze implement at Ban Chiang – a bent-tip spear point.

The few exceptional values among females include Burial BCES 34 (EP IV), with a high $^{87}\text{Sr}/^{86}\text{Sr}$ value (0.71290) and the least-negative $\delta^{13}\text{C}$ (−11.8) of our entire sample, which is the only Ban Chiang female buried in a flexed body position. The less negative $\delta^{13}\text{C}$ value for BCES 34 may reflect her having subsisted on foods grown in more open conditions or at higher altitude. As a group, the flexed burials show a high frequency of pathological conditions and skeletal/dental anomalies, which may reflect their exogenous origins (Pietruszewsky & Douglas 2002: 179). Burial BCES 1, a young female from LP X, is an extreme outlier in both $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ values ($^{87}\text{Sr}/^{86}\text{Sr} = 0.72588$, $\delta^{18}\text{O} = 24.71$), and it is notable that the third-highest $^{87}\text{Sr}/^{86}\text{Sr}$ value (0.71304) we measured is also from LP X (BCES 2, a middle-aged male).

Differences between BC and BCES

Finally, the isotope data suggest different neighbourhoods at Ban Chiang. While the mean isotope values over all phases are not significantly different between the BC and BCES locales, the variance in $^{87}\text{Sr}/^{86}\text{Sr}$ for BC (mean 0.71171 ± 0.00076 , $n = 16$) is significantly ($p < 0.05$) larger than it is for BCES ($^{87}\text{Sr}/^{86}\text{Sr} = 0.71175 \pm 0.00051$, $n = 25$ excluding BCES 1), with the difference even more significant for Phase EP V alone ($p < 0.03$). Furthermore, in the phases with an adequate sample of both BC and BCES individuals (EP II/III and EP V), both the highest and lowest $^{87}\text{Sr}/^{86}\text{Sr}$ values overall are from BC burials (Figures 2c and 2d combined). Perhaps the wider variance in $^{87}\text{Sr}/^{86}\text{Sr}$ values from BC relative to BCES reflects a community of outsiders at BC, which would be consistent with the burial orientation differences.

Interpretation

The isotope evidence offers a significant contribution to the early history of the population in this part of Thailand, during the period of increasing agricultural intensification in the region. Around the period marked by phases EP IV-V at Ban Chiang, a group of men with non-local isotope signatures are also those buried with bronze weapons. There is also one non-local woman, the only one to be buried in a flexed position. During and after EP V, the range of $^{87}\text{Sr}/^{86}\text{Sr}$ among females, as opposed to males, is considerably reduced. This might suggest an increasing sexual division of labour, such that boys ranged over a wide area while hunting and gathering (supported by males' slightly less-negative $\delta^{13}\text{C}$ values in EP V), and women remained closer to the settlement. Alternatively, these results might reflect a cultural pattern of matrilocality, by which the man immigrates to the woman's birthplace after marriage. In fact, the two hypotheses are complementary, since prolonged male absence on hunting expeditions encourages matrilocality because it leaves women to manage the interests of their kin (Trigger 1978; Harris 1980; Hage & Marck 2003). Furthermore, while over 70 per cent of the world's societies are patrilocal, inferences from genetics and linguistics generally indicate a long history of matrilocality in Southeast Asia (e.g. Tajima *et al.* 2002; Fucharoen *et al.* 2001; Hage & Marck 2003; Burton *et al.* 1996; Oota *et al.* 2001).

In contrast to the evidence from Ban Chiang, strontium isotope evidence from early Neolithic skeletons of central Europe, where the transition to agriculture occurred much more rapidly, reveals a high incidence of non-local females (Bentley *et al.* 2002). Possibly, a prevailing cultural pattern of patrilocality led to a rapid transition to farming in Neolithic Europe. If livestock wealth is usually transferred paternally (Holden & Mace 2003), a patrilocal marital residence pattern may have hastened the spread of agriculture into regions of indigenous hunter-gatherers. This is because, in cases of contact, exchange between farmers and foragers often eventually favours the farmers, and as forager women then immigrate into farming communities, by choice or through bride exchange, unmarried forager men are pressured to farm in order to compete for a bride (e.g. Cronk 1989; Hoffman 1984; Peterson 1978; Spielmann & Eder 1994; Zvelebil & Lillie 2000).

Since marriages between forager women and farmer/pastoralist men occur most often when fertility is low in the farmers' community (Bailey 1988), it may be that those small groups of immigrant farmers into which indigenous women married were the ones to survive

in early Neolithic Europe. This could partly explain why mtDNA (e.g. Torroni *et al.* 1998; Richards *et al.* 2000) and Y-chromosome distributions (Semino *et al.* 1996; Chikhi *et al.* 2002; Rosser *et al.* 2000) differ on the continental scale among modern Europeans (Bentley *et al.* 2003b; Seielstad *et al.* 1998; Wilson *et al.* 2001). While matrilocality prevailed in Southeast Asia, there was less chance for females to emigrate to farmer communities, and hunting and gathering may have persisted with opportunities to trade with agricultural groups perhaps as early as the mid third millennium BC (Headland & Reid 1989; Kealhofer 2002).

In conclusion, the isotopic evidence from Ban Chiang skeletons is consistent with a transition to matrilocality that, if true, suggests a potential link between marital residence pattern and the prehistoric spread of agriculture. This isotope research has only just begun, however, and there are still many other explanations for these data that, strictly speaking, identify a transition to local isotope signatures among females during their pre-adolescence that does not occur among males. The isotope data do not yet falsify, for example, a devil's-advocate hypothesis that Ban Chiang was quite male-centred and patrilocal, and girls were restricted to locally gathered foods whereas boys could eat meat from distant hunts. Clearly, the way forward is further research on how these and other people acquired their isotope signatures; future work is aimed towards characterising the study regions through geographically distributed samples of archaeological fauna (cf. Bentley *et al.* 2004; Bentley & Knipper 2005) and sampling at additional sites spanning the transition to intensified agriculture (e.g. Bentley 2004). Also, the data so far provide particularly promising hypotheses for future ancient DNA analysis of the same skeletons, as any genetic similarities or differences identified among isotopic locals versus non-locals could provide a breakthrough in understanding this important demographic transition.

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